Formation, Detection, and Characterization of Extrasolar Habitable Planets
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Climate of Extraterrestrial Planets with Oceans and Carbonate-Silicate Geochemical Cycle Under Various Obliquities

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Abstract. We systematically investigated the climate of water-rich terrestrial planets with a negative feedback mechanism of carbonate-silicate geochemical cycle against the climate under various obliquities and semi-major axes. We found that, while the permanent ice-cap mode (partially ice-covered throughout the year) and the seasonal ice-cap mode (partially ice-covered seasonally) exist stably at low obliquity conditions, the ranges of semi-major axis for these climate modes shrink and finally disappear with an increase of obliquity. When carbonate-silicate geochemical cycle is taken into account, the ranges of semi-major axis for all the climate modes expand at any obliquities, compared with the cases without carbonate-silicate geochemical cycle, indicating that the carbonate-silicate geochemical cycle strongly stabilizes the climate for the planets with any obliquities inside the habitable zone.

Keywords. astrobiology, planets and satellites: general, Earth

1. Introduction

Water-rich terrestrial planets like Earth are expected to be found in the extrasolar planetary systems in the near future. In order to understand habitability of such planets, we have to investigate characteristic features of climate modes of the planets under various conditions. Obliquity, an inclination of planetary axis, is one of the most important factors which controls the climate mode. Obliquity variation could induce large climate changes owing to seasonality and changes of meridional distribution of insolation on the planetary surface. The climate of Earth has been stabilized on a long timescale by a negative feedback mechanism in the carbonate-silicate geochemical cycle (hereafter, carbon cycle) system, involving removal of CO_2 from the atmosphere by chemical weathering and runoff, and supply of CO_2 from the Earth's interiors to the atmosphere via volcanism (Walker *et al.* 1981). Earth-like habitable planets should have a similar mechanism.

The climate of oblique planets has been studied previously (e.g., Williams & Kasting 1997; Williams & Pollard 2003; Spiegel *et al.* 2009), there are no comprehensive studies to discuss long-term stability of climate of extraterrestrial planets with various obliquities. Therefore, in this study, we systematically investigate the long-term stability of climate of the Earth-like planets with carbon cycle under various obliquities and semi-major axes.

2. Model Description

Governing Equation. Here we use a 1-dimensional energy balance climate model (EBM) (Williams & Kasting 1997). Heat capacity and albedo used in this study are summarized

Table 1. Heat capacity and albedo

	Ocean		Land	
T [a]	C [b]	A [c]	C [b]	A [c]
$T > 273$[K]	$40C_l$ [d]	0.30[e]	C_l [d]	0.20 [e]
$263 < T \leqslant 273$[K]	$9.2C_l$ [d]	0.62 [e]	C_l [d]	0.62 [e]
$T \leqslant 263$[K]	$2C_l$ [d]	0.62 [e]	C_l [d]	0.62 [e]

Note: [a] Temperature [K].
[b] Heat capacity [$Jm^{-2}K^{-1}$].
[c] Surface albedo.
[d] Williams & Kasting (1997).
[e] North *et al.* (1981).

Table 2. Constants of the planet

Parameter	Value
Eccentricity (e)	0
Solar constant (S_0)	1370 W/m^2 at 1 AU
Rotation period	24 hours
Relovution period	365 solar days at 1 AU
Net CO_2 supply	6.65×10^{12} mol/year [1]

Note: [1] Berner (1994)

Table 3. Ranges of obliquity and semi-major axis investigated in this study

Parameter	Value	Range
Obliquity (δ_0)	0° - 90°	2°
Semi-major axis (a)	0.90AU - 1.40AU	0.01AU

in Table 1. The atmosphere is composed of 1 bar of N_2 as a noncondensable gas, and CO_2 and H_2O as condensable gases. The amount of CO_2 in the atmosphere is determined by the balance of silicate weathering rate and degassing rate of CO_2 via volcanism through carbon cycle (See Walker *et al.* 1981). The expression of silicate weathering rate is adopted from Walker *et al.* (1981).

Description of the planet. The constants used in this model are shown in Table 2. We change obliquity and semi-major axis systematically as shown in Table 3. For simplicity, we assume the continental distribution as a fraction 0.3 for each latitude.

3. Results and Discussion

Classification of climate modes. We hereby categorize climate modes as follows; Runaway-greenhouse mode as short wave income, large enough to cause runaway greenhouse (the solar flux is more than 1.4 S_0) (Kasting *et al.* 1993), ice-free mode as no ice cover throughout the year, seasonal-ice-cap mode as the planet covered seasonally and partially with ice, permanent-ice-cap mode as the planet covered partially with ice throughout the year, snowball mode as a cycle of ice-covered state and ice-free state for a geological time scale, and permanent-snowball mode as the planet too cold to escape from snowball state.

Characteristic features of climate modes. Permanent-ice-cap mode and seasonal-ice-cap mode exist only at lower obliquities (Figs. 1 & 2). This is because, with the increase of obliquity, the difference between insolation received at polar region and equatorial region decreases, resulting in meridional heat transport to be insufficient. When carbon cycle is taken into account, the ranges of semi-major axis for all the climate modes expand at any obliquities, compared with the cases without carbon cycle (Fig. 2), as a result of pCO_2 equilibrium level controlled by carbon cycle (Fig. 3). This indicates that the carbon cycle strongly stabilizes the climate for the planets with any obliquities inside the habitable zone. The CO_2 level does not seem to depend on obliquity strongly, even if the climate mode is different. This is because, with an increase in obliquity, a decrease of silicate weathering rate at low latitude may tend to be compensated by an increase of silicate weathering rate at high latitude of summer hemisphere (Fig. 4).

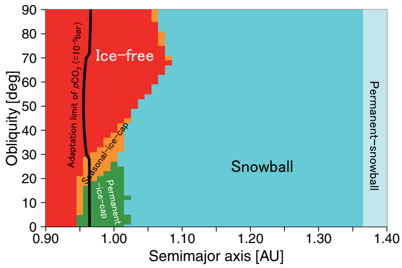

Figure 1. Climate mode diagram for the planet with carbon cycle.

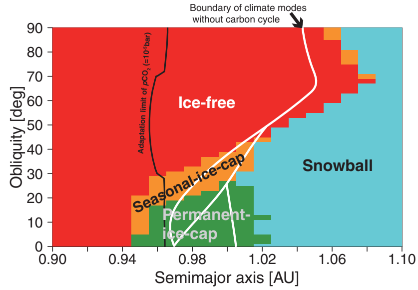

Figure 2. Climate mode diagram for the planet without carbon cycle (atmospheric pCO_2 fixed at 280 ppm) plotted on Fig. 1.

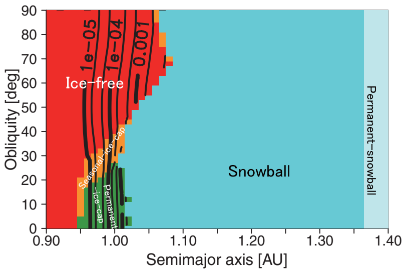

Figure 3. Atmospheric CO_2 equilibrium level (in bar) plotted on Fig. 1.

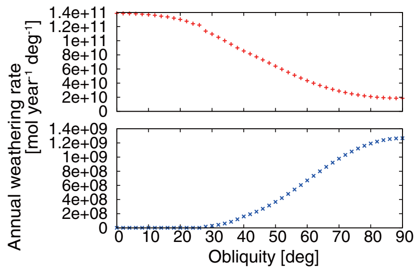

Figure 4. Annual silicate weathering rate at equator (top) and at pole (bottom) for a = 1.0AU.

4. Conclusion

We have investigated the climate of water-rich extraterrestrial planets systematically with various obliquities and with carbon cycle. We obtained the following results: While the permanent ice-cap mode (partially ice-covered throughout the year) and the seasonal ice-cap mode (partially ice-covered seasonally) exist stably at low obliquity conditions, the ranges of semi-major axis for these climate modes shrink and finally disappear with an increase of obliquity. If the carbon cycle is taken into account, the ranges of semi-major axis for all the climate modes expand at any obliquities, compared with the cases without carbon cycle, indicating that the carbon cycle strongly stabilizes the climate for the planets with any obliquities inside the habitable zone. The CO_2 level does not strongly depend on obliquity.

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